Photoresponse of GaAs/AlAs heterostructures under external bias

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Results of a photoresponse technique which has been employed to study the photovoltaic properties of GaAs/AlAs heterostructures are presented. The structures consist of a thin layer of AlAs (50 or 200 Å thick) sandwiched between layers of GaAs which were several microns thick. The experimental procedure consisted of illuminating these structures with chopped light while also applying a constant dc bias across the samples. The resulting photovoltage across the sample was then measured as a function of the wavelength of the incident light. It has been found that the application of a dc bias can increase (by several orders of magnitude in some cases) the magnitude of the photovoltage signal compared with that observed when no dc bias is applied. The dc bias was found to shift the photovoltage spectrum to slightly longer wavelengths.

I. INTRODUCTION

In previous publications, we have discussed a photoresponse technique which we have employed to study GaAs/AlAs heterostructures.[1,2] In these experiments, we have studied samples consisting of thin layers of AlAs sandwiched between layers of GaAs a few microns thick. These samples were illuminated with chopped light, and the resulting photovoltage was measured as a function of the wavelength of the incident light. In this paper, we extend these results to the case where we apply a dc bias across the samples. We detect only the photovoltage by measuring only that component of the voltage across the sample which is at the same frequency and in phase with the incident light. The basic results presented in this paper can be summarized as follows. The application of a dc bias (0.5 V or less) increases (by several orders of magnitude in some cases) the magnitude of the photovoltage signal as compared to that observed when there is no bias applied. The photovoltage spectrum is generally a peak, and this peak shifts to slightly longer wavelengths with the application of larger (2.0 V) biases. For these larger biases, we also observe a decaying photoresponse signal at wavelengths longer than that of the peak which is not present when no bias is applied.

II. EXPERIMENTAL

The samples used in this study were grown by a metalorganic chemical vapor deposition technique.[3,4]. The effects observed, which will be discussed in detail below, were common to many samples studied, but we limit our discussion here to two samples in particular. Both samples were grown on a GaAs substrate which was doped *n* type at about 3×10^{18} cm^{-3} with Si. The first (Sample 1) had an AlAs layer about 200 Å thick doped *p* type at about 1×10^{18} cm^{-3} with Mg.[5,6] The GaAs cladding layers, which were a few microns thick, were degenerately doped *n* type at about 5×10^{17} cm^{-3} with Se. The second sample (Sample 2) had an AlAs layer 50 Å thick also doped *p* type at about 1×10^{18} cm^{-3}. The GaAs cladding layers were degenerately doped *n* type at about 5×10^{18} cm^{-3} with Se. Ohmic contacts were made to the samples by evaporation of a Au/Ge alloy followed by a 20 s anneal at 420 °C. Photolithographic techniques were employed to define ring shaped contacts on the front surface of the sample to allow light to penetrate into the GaAs. To apply the biases we used an HP model 6002A dc power supply with a resistor in series with the sample. When this resistor is greater than the sample impedance but less than the input impedance of the lock-in amplifier, the full photovoltage is measured across the lock in. Further details of the contacts and the experimental procedure can be found in Refs. 1 and 2.

III. RESULTS AND DISCUSSION

In Fig. 1, we present photovoltage spectra taken for Sample 1 at 6 and 300 K with the applied biases noted in the figure. These spectra have been scaled so as to display the relative signal strengths. We note, first, a large increase in the signal at 6 K (approximately five times) with the applied bias as compared to the signal when we do not apply a bias. At 300 K we see that with the application of the dc bias, we measure a photovoltage signal which we cannot measure

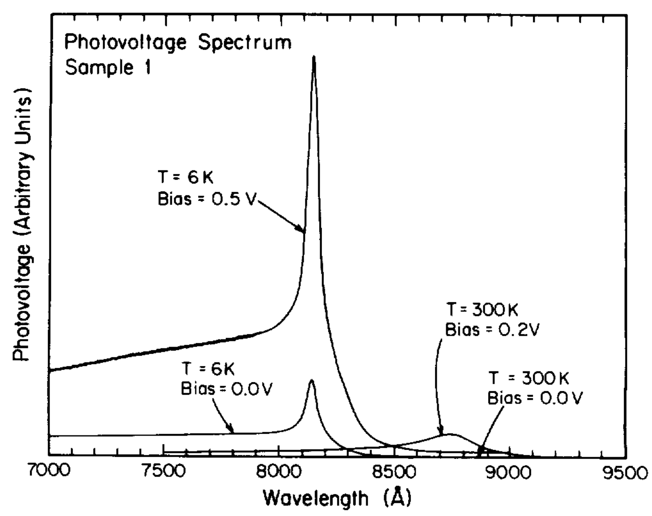

FIG. 1. Photovoltage spectra taken for the biases and at the temperatures indicated. The AlAs layer thickness is 200 Å. The GaAs layers are doped *n* type at 5×10^{17} cm^{-3}.

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above the noise level without the application of the bias. Note also that in general we observe a greater photovoltage for a greater applied bias. It is unlikely that exciton absorption is the process which creates the charge carriers which produce the photovoltage since the GaAs is degenerately doped. In our earlier work, we proposed the following mechanism to account for the photovoltage signal which is observed for zero applied bias. Electrons excited in the conduction band of the GaAs by free carrier absorption to energies greater than that presented by the AlAs barrier flow across the AlAs layer and thus produce the observed voltage. The driving force for this flow of electrons from the illuminated side of the barrier to the back of the barrier is the greater concentration of optically excited electrons on the front side of the AlAs layer than on the back side of the barrier. This difference in the concentration of optically excited electrons is a result of the difference in the integrated light intensity on either side of the barrier. We showed by a model calculation that the photovoltage spectrum followed the difference in light intensity on either side of the barrier as a function of the wavelength of the light. To account for the increase in signal under a nonzero applied dc bias, we propose the following mechanism. The dc bias causes a certain amount of accumulation of electrons to take place on one side of the barrier and causes a depletion of electrons on the other side of the barrier. This charge redistribution takes place very near (within 100 Å) the barrier so that the bulk optical properties of the structure are not greatly affected for small biases (0.5 V or less). However, now, when there is a difference in the integrated light intensity on either side of the barrier, there is an even greater difference in the number of electrons which can be optically excited and then flow across the barrier. This enhanced difference in the number of electrons excited on either side of the barrier causes the enhanced photovoltages which we observe. We conclude that the bulk optical properties of the samples are not greatly affected by the application of small biases (less than 0.5 V), because of the fact that the spectra for samples under bias and not under bias look very much the same except for their relative magnitude. We have observed that when the sign of the applied dc bias is reversed, the sign of the photovoltage is reversed. We have also observed that when the samples are biased with the illuminated side of the barrier negative and the back of the barrier positive (accumulation on the illuminated side), we measure a stronger photovoltage than when the sign of the dc bias is reversed. The overall shift of the spectra between 6 and 300 K results from the change in the band gap of the GaAs which determines its fundamental absorption edge. This, in turn, determines at which wavelength there is the greatest difference in the light intensity in front of and behind the barrier. This has been discussed in Ref. 2. Typically we find that depending on the sample, between 10^{-3} and 10^{-2} electrons per photon are producing the observed photovoltage.

In Fig. 2, we present the photovoltage spectra for Sample 2 at 6 and 300 K. In this sample, there is no measurable signal above the noise when no bias is applied. Again, these spectra have been plotted so as to represent the relative magnitudes of the signals. We also note in this figure as well as Fig. 1 that the peak seen at 300 K is broader than that at 6 K.

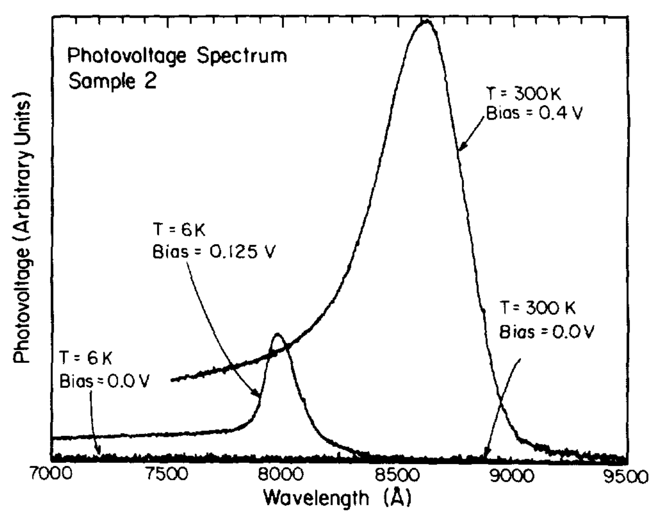

FIG. 2. Photovoltage spectra taken for the biases and at the temperatures indicated. The AlAs layer thickness is 5 Å. The GaAs layers are doped *n* type at 5×10^{18} cm^{-3}. Note the increased peak width at the higher temperature.

We account for this as being a result of the fact that at higher temperatures the electron distribution in the conduction band of the GaAs is broadened out due to the thermal energy of the electrons. This broadens the fundamental absorption edge of the GaAs. Hence, the wavelengths where we have a maximum difference in the light intensity on either side of the AlAs barrier are spread out.

In Fig. 3, we present two photovoltage spectra for Sample 1 both taken at 6 K, but one for zero applied dc bias and the other for an applied dc bias of 1.95 V. This applied bias is substantially larger than those applied in the spectra presented in Figs. 1 and 2. In this figure, the spectra have been normalized so as to have the same apparent magnitude. There are two points of particular interest in this figure. The first is the shift of the peak position to slightly longer wavelengths in the photovoltage spectrum which was taken with

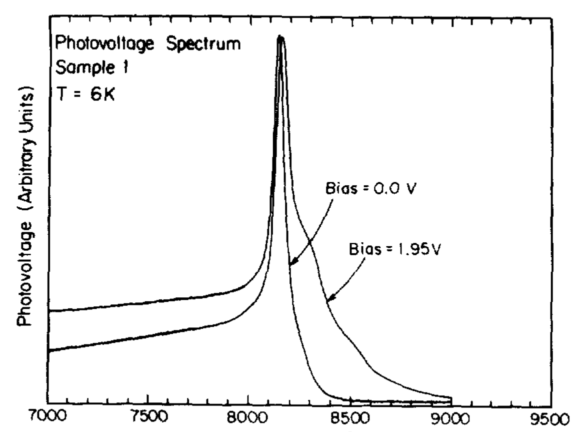

FIG. 3. Photovoltage spectra for sample 1 (AlAs layer 200 Å thick). We compare here two spectra, normalized so as to have the same apparent magnitude, for zero applied bias and a large applied bias. Note, for the spectra taken with the applied bias, the shift in the peak position to longer wavelengths and the long wavelength tail on the photovoltage spectrum.

the applied bias as compared to that taken with no applied bias. The second is the very pronounced signal at long wavelengths past the peak that is developed on the spectrum. The signal on this tail is much below the GaAs band gap at 6 K, which is about 8162 Å. Both of these features, we believe, can be explained in terms of the Franz–Keldysh effect[7], that is, the band gap narrowing that takes place in the GaAs as a result of the presence of the large electric fields which are present due to the applied bias. When a dc bias is applied across such a heterostructure, a certain fraction of the voltage is dropped in the depleted GaAs region. This is due to the fact that in order to drop a voltage across the AlAs barrier we must have positive and negative charges on either side of the barrier. On the side of the AlAs barrier where depletion takes place, we can only have, in this case, 5×10^{17} ionized donors per cubic centimeter. This produces a depletion region of significant width in which there must be an electric field. By a very rough estimate, we find that the electric field in this region can be on the order of 100 $\mathrm{KV}\cdot\mathrm{cm}^{-1}$, certainly enough to create an effective band gap narrowing in this region. When this happens, the optical absorption edge in this region of the GaAs is moved to longer wavelengths. Thus, the wavelengths at which there is a difference in the number of optically excited electrons on either side of the barrier are shifted to longer wavelengths and so is the resulting photovoltage spectrum which we measure. The undulations seen on the long wavelength tail of the spectrum in Fig. 3 for the sample under bias are not predicted by the Franz–Keldysh effect. We believe that these undulations are the result of optical etaloning taking place in the sample due to the spatial variations of the absorption in the GaAs which results from the charge redistribution taking place under bias. We have observed similar undulations in the photovoltage spectra of samples taken not under bias in our earlier work.[1,2]

IV. SUMMARY

In summary, we have presented experimental results of a photoresponse technique which we have employed to study some of the photovoltaic properties of GaAs/AlAs heterostructures, consisting of a thin layer of AlAs sandwiched between thick GaAs layers. We have shown that the application of a dc bias to these structures results in a marked increase in the strength of the observed photovoltage as compared to that observed with no applied dc bias. We have proposed that the increase in the photovoltage signal is a consequence of the accumulation of electrons on one side of the barrier and the depletion of electrons on the other side of the barrier. This charge redistribution enhances the difference in the integrated number of optically excited electrons on either side of the barrier. For larger applied biases, we have shown that the photovoltage spectrum is shifted to slightly longer wavelengths, and there is an added long wavelength tail on the photovoltage spectrum. The latter two effects we have proposed are a result of the effective band gap narrowing in the depleted GaAs due to the presence of large electric fields in this region.

We believe that optical experiments of this nature will be useful in determining some of the more fundamental properties of these heterostructures. By understanding the optical properties of these structures, we may then be able to measure such quantities as the band offsets, or observe processes such as electronic interference effects. In general, the application of these techniques to more varied structures should yield many interesting results.

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